The search for nonstandard Higgs bosons at FNAL and LHC

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Abstract

We discuss the phenomenology of many Higgs doublet model - the model where each Higgs doublet couples with each own quark and lepton with relatively big Yukawa coupling constants. Namely, we discuss the discovery potential of the Higgs bosons at LHC and find lower mass limits on nonstandard Higgs bosons from FNAl data.

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The aim of this paper is the discussion of the phenomenology of many Higgs doublet models [1]-[14]. We shall restrict ourselves to many Higgs doublet models where each Higgs doublet couples with its own quark with relatively big Yukawa coupling constant. Many Higgs doublet models naturally arise in some nonsupersymmetric and supersymmetic GUT models [12]-[14]. Here we consider the phenomenology of many Higgs doublet models. Namely, we discuss the discovery potential of the Higgs bosons with relatively big Yukawa coupling constants with quarks at LHC and find lower mass bound for nonstandard Higgs bosons from FNAL data.

To be precise in this paper we consider the model with 6 Higgs doublets [12]-[14] where each Higgs doublet couples with its own quark and lepton. The Yukawa Lagrangian of the model has the form

$$L_Y = \sum_{i,j=1}^{3} [h_{ij}^u \overline{A}_{Li} u_{Rj} H_{ju} + h_{ij}^d \overline{A}_{Li} d_{Rj} H_{jd} + h_{ij}^l L_{Li} e_{Rj} H_{jd}] + h.c. \;, \tag{1}$$

where $A_{L1} = (u,d)_L$, $A_{L2} = (c,s)_L$, $A_{L3} = (t,b)_L$, $u_{R1} = u_R$, $u_{R2} = c_R$, $u_{R3} = t_R$, $d_{R1} = d_R$, $d_{R2} = s_R$, $d_{R3} = b_R$, $H_{1u} = (H_{uu}, H_{ud})$, $H_{2u} = (H_{cc}, H_{cs})$, $H_{3u} = (H_{tt}, H_{tb})$, $H_{1d} = (H_{du}, H_{dd})$, $H_{2d} = (H_{sc}, H_{ss})$, $H_{3d} = (H_{bt}, H_{bb})$

The Lagrangian (1) is invariant under the transformations

$$H_{ju} \to exp(i\alpha_j) H_{ju} \;, \tag{2}$$

$$H_{jd} \to exp(i\beta_j) H_{jd} \;, \tag{3}$$

$$u_{Rj} \to exp(-i\alpha_J) u_{Rj} \;, \tag{4}$$

$$d_{Rj} \to exp(-i\beta_j) d_{RJ} \;, \tag{5}$$

$$e_{Rj} \to exp(-i\beta_j) e_{Rj} \tag{6}$$

To get rid of the problems with neutral flavor changing currents [1, 2] we postulate that the matrices h_{ij}^u, h_{ij}^d and h_{ij}^e are unitare. After the diagonalization of the mass matrices we find that in considered model each quark interacts with its own higgs doublet . We assume that all Yukawa coupling constants in the diagonal basis are not small and the

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difference in masses between different quarks and leptons is due to the difference in vacuum expectation values for different Higgs doublets. The Higgs potential has the form

$$V = \lambda (H_{3u}^+ H_{3u} - c^2)^2 + L_M + \delta L, \qquad (7)$$

$$L_M = M_{2u}^2 H_{2u}^+ H_{2u} + M_{1u}^2 H_{1u}^+ H_{1u} + M_{3d}^2 H_{3d}^+ H_{3d} + M_{2d}^2 H_{2d}^+ H_{2d} + M_{1d}^2 H_{1d}^+ H_{1d} , \qquad (8)$$

$$\delta L = -(\overline{H}_{3u}^+ [m_1^2 H_{1d} + m_2^2 H_{2d} + m_3^2 H_{3d} + m_4^2 \overline{H}_{1u} + m_5^2 \overline{H}_{2u}] + h.c.) , \qquad (9)$$

$$\overline{H}_i = \epsilon^{ij} H_j^+ \qquad (10)$$

The term δL violates the discrete symmetry (3) in a soft way. At the first stage of the symmetry breaking only H_{3u} Higgs doublet acquires a nonzero vacuum expectation value that leads to the electroweak symmetry breaking and to the generation of the t-quark mass. Due to the soft mass term δL after the first stage of breaking other Higgs doublets acquire nonzero vacuum expectation values

$$< H_{1d} >= \frac{m_1^2}{M_1^2} < \overline{H}_{3u} >, ..., \qquad (11)$$

For nonsmall Yukawa coupling constants the main reaction for the production of the Higgs doublets corresponding to the first and second generations is quark-antiquark fusion. The phenomenology of the Higgs doublet corresponding to the third generation is very similar to the phenomenolgy of the standard 2 Higgs doublet model and we shall not discuss it. The cross section for the quark-antiquark fusion in quark-parton model is given by the standard formula [15]

$$\sigma(AB \to H_{q_i q_j} + X) = \frac{4\pi^2 \Gamma(H_{q_i q_j} \to \overline{q}_i q_j)}{9 M_H^3} \int_{\frac{M_H^2}{s}}^1 [\overline{q}_{Ai}(x, \mu) q_{Bj}(x^{-1} M_H^2 s^{-1}, \mu)$$

$$+ q_{Aj}(x, \mu) \overline{q}_{Bj}(x^{-1} M_H^2 s^{-1}, \mu)] \qquad (12)$$

Here $\overline{q}_{Ai}(x, \mu)$ and $q_{Aj}(x, \mu)$ are parton distributions of the antiquark $\overline{q}_i$ and quark q_j in hadron A at the normalization point $\mu \sim M_H$ and the $\Gamma(H_{q_i q_j} \to \overline{q}_i q_j)$ is the hadronic decay width of the Higgs boson into quark-antiquark pair. For the Yukawa Lagrangian

$$L_Y = h_{q_i q_j} \overline{q}_{Li} q_{RJ} H_{q_i q_j} + h.c. \qquad (12)$$

the hadronic decay width for massless quarks is

$$\Gamma(H_{q_i q_j} \rightarrow \overline{q}_i q_j) = \frac{3 M_H h_{q_i q_j}^2}{16\pi} \tag{13}$$

We have calculated the cross sections for the Higgs production using the parton distributions of ref.[16]. We have used both set1 and set2 of ref.[16]. The results of our calculations are presented in tables 1 - 6. It should be noted that the results presened in tables 1 - 6 correspond to the Yukawa coupling constants $h_{ij}^2 = 1$. For the case of arbitrary Yukawa coupling h_{ij} the corresponding cross section σ_{ij} is proportional to h_{ij}^2. In our calculations we took the value of the renormalization point μ equal to the mass M of the corresponding Higgs boson. We have checked also that the variation of the renormalization point μ in the interval $0.5M - 2M$ leads to the variation of the cross sections less than 50 percent. In considered model Higgs bosons couple both with quarks and leptons so the best signature is the search for the Higgs boson decays into lepton pairs for electrically neutral Higgses. For charged Higgses the best way to detect them is to look for their decays into charged leptons and neutrino. The Higgs doublets which couple with up quarks in model with massless neutrino don't couple with leptons so the single way to detect them is to look for the resonance type structure in the differential dijet cross section on the dijet mass as in the case of all Higgs bosons , since in considered model all Higgs bosons decay mainly into quark-antiquark pair that leads at the hadron level to the dijet events. However the accuracy of the determination of the dijet cross section is not very high and besides the typical accuracy in the determination of the dijet invariant mass is $O(10)$ percent so it is difficult to find stringent bound on the Higgs mass by the measurement of dijet differential cross section. It should be noted that in considered many Higgs doublet model due to the smallness of the vacuum expectation values of the Higgs doublets corresponding to the u,d,s and c quarks after the electroweak symmetry breaking the mass splitting inside the Higgs doublets is small, so in such models the search for neutral Higgs boson decaying into lepton pair is in fact the search for the Higgs isodoublet as a whole. Consider the electrically neutral Higgs boson that couples with strange quark and μ-meson. For the s-quark mass [17] $m_s(1Gev) = (150 - 200)\ Mev$ after taking into account QCD evolution of the

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running quark mass we find that $Br(H_{ss} \to \mu^+ \mu^-) = (0.3 - 0.6)$. So by the measurement of muon pairs we can look for the corresponding Higgs boson. The main background comes from the Drell-Yan process but for relatively big value of the Yukawa coupling constant $h^2 \geq O(10^{-3})$ the Drell-Yan background is small. For the Higgs field which couples with d-quark and electron for the d-quark mass [18] $m_d(1 Gev) = (5 - 10) Mev$ we find that $Br(H_{dd} \to e^+ e^-) = (0.5 - 1) \cdot 10^{-2}$, so again by the measurement of the electron-positron invariant mass pair we can detect the Higgs bosons or to derive the lower bound on their masses.

FNAL data [18] on dilepton production agree with the predictions of the standard Weinberg-Salam model. From our calculations of the cross sections of the production of the Higgs bosons (see tables 1 - 6) requiring the existence of less than 10 events with muon antimuon or electron positron pairs for the integrated luminosity of 70 inverse pikoborn at FNAL $p\overline{p}$ collider we find that

$$M_{H_{ss}} \geq 400 \, Gev \,, \tag{14}$$

$$M_{H_{dd}} \geq 400 \, Gev \tag{15}$$

for $h_{ss} = h_{dd} = 1$ and

$$M_{H_{ss}} \geq 300 \, Gev \,, \tag{16}$$

$$M_{H_{dd}} \geq 280 Gev \tag{17}$$

for $h_{ss}^2 = h_{dd}^2 = 0.1$. In fact, the strategy of the search for additional Higgs doublets with big Yukawa couplings by the measurement of dilepton mode at supercolliders is very similar to the strategy of the search for the additional neutral vector bosons at supercolliders by the measurement of dilepton mode [17, 18]. Recently obtained FNAL bound $M_{Z'} \geq 650 \, Gev$ [18] for new neutral Z'-boson (in the assumption that quark and lepton coupling constant of Z'-boson coincide with the corresponding coupling constants of Z-boson) are slightly more stringent that our bounds (15-19).

For LHC for full integrated luminosity $\int L = 10^5 (pb)^{-1}$ and for $\sqrt{s} = 15 \, Tev$ requiring the existence of 100 events with lepton pairs we find that for the integrated luminosity

$L = 10^5 (pb)^{-1}$ it would be possible to discover the Higgs bosons H_{ss} and H_{dd} with the masses up to 3000 Gev for $h^2 = 1$ and with the masses up to 2000 Gev for $h^2 = 0.1$. It should be noted that the main background comes from the Drell-Yan process however for not very small $h^2 \geq O(10^{-3})$ Yukawa coupling constants and for the measurement of dilepton mass with the accuracy better than 2 percent the background is small.

To conclude, in this note we have studied the perspectives of the discovery of the nonstandard Higgs bosons, namely Higgs bosons whith relatively big Yukawa coupling constant with quarks at LHC. The best way to detect such Higgs bosons is the measurement of the dilepton invariant masses. We have found also that FNAL data lead to the bounds (15-19) on the nonstandard Higgs bosons. LHC will be able to discover the nonstandard Higgs bosons with masses up to 2-3 Tev.

Table 1. The cross sections $\sigma(p\overline{p} \to H_{ij} + ...)$ in pb for different values of the Higgs boson masses for Yukawa coupling constants $h_{ij}^2 = 1$ and for normalization point $\mu = M_H$ at FNAL (set 1).

M(Gev)	σ_{cc}	σ_{ss}	σ_{uu}	σ_{dd}	σ_{ud}	σ_{sc}
1000	$9.5 \cdot 10^{-8}$	$5.1 \cdot 10^{-7}$	0.11	0.0053	0.025	$2.2 \cdot 10^{-7}$
900	$1.0 \cdot 10^{-6}$	$6.5 \cdot 10^{-6}$	0.43	0.025	0.11	$2.6 \cdot 10^{-6}$
800	$9.5 \cdot 10^{-6}$	$6.8 \cdot 10^{-5}$	1.4	0.11	0.41	$2.6 \cdot 10^{-5}$
700	$8.2 \cdot 10^{-5}$	$6.2 \cdot 10^{-4}$	4.5	0.44	1.5	$2.3 \cdot 10^{-4}$
600	$6.9 \cdot 10^{-4}$	0.0053	13	1.7	4.9	0.0013
500	0.0067	0.044	39	6.3	16	0.016
400	0.057	0.39	120	24	55	0.15
300	0.65	3.7	390	100	200	1.6
200	10	48	$1.6 \cdot 10^3$	560	$0.97 \cdot 10^3$	22
150	53	220	$4.0 \cdot 10^3$	$1.6 \cdot 10^3$	$2.6 \cdot 10^3$	110

Table 2. The same for FNAL (set 2)

M(Gev)	σ_{cc}	σ_{ss}	σ_{uu}	σ_{dd}	σ_{ud}	σ_{sc}
1000	$2.5 \cdot 10^{-6}$	$7.7 \cdot 10^{-6}$	0.12	0.067	0.029	$4.4 \cdot 10^{-6}$
900	$2.0 \cdot 10^{-5}$	$6.0 \cdot 10^{-5}$	0.43	0.033	0.12	$3.5 \cdot 10^{-5}$
800	$1.4 \cdot 10^{-4}$	$4.1 \cdot 10^{-4}$	1.4	0.14	0.46	$2.4 \cdot 10^{-4}$
700	$8.4 \cdot 10^{-4}$	0.0027	4.4	0.54	1.6	0.0013
600	0.0053	0.016	13	2.0	5.2	0.0093
500	0.029	0.095	37	7.3	17	0.053
400	0.19	0.63	110	27	56	0.35
300	1.4	4.9	360	110	200	2.6
200	16	54	$1.5 \cdot 10^3$	580	$0.93 \cdot 10^3$	28
150	61	230	$3.6 \cdot 10^3$	$1.6 \cdot 10^3$	$2.4 \cdot 10^3$	120

Table 3. The cross sections $\sigma(pp \rightarrow H_{ij} + ...)$ in pb for different values of the Higgs boson masses for Yukawa coupling constants $h_{ij}^2 = 1$ and for the renormalization point $\mu = M_H$ at LHC (set 1, $\sqrt{s} = 10\,Tev$).

M(Gev)	σ_{cc}	σ_{ss}	σ_{uu}	σ_{dd}	σ_{sc}
3000	$3.1 \cdot 10^{-6}$	$5.2 \cdot 10^{-4}$	0.040	0.12	$4.0 \cdot 10^{-5}$
2000	$6.3 \cdot 10^{-4}$	0.027	0.83	0.32	0.0041
1500	0.011	0.24	4.4	1.9	0.049
1200	0.064	0.97	13	5.9	0.25
1000	0.24	2.8	29	14	0.81
800	1.0	8.8	75	37	3.1
600	5.4	35	220	120	13
500	14	76	430	240	32
400	41	190	940	540	88
300	140	580	$2.5 \cdot 10^3$	$1.5 \cdot 10^3$	290

Table 4. The same for LHC (set 2, $\sqrt{s} = 10Tev$)

M(Gev)	σ_{cc}	σ_{ss}	σ_{uu}	σ_{dd}	σ_{sc}
3000	$2.3 \cdot 10-4$	0.0040	0.096	0.033	$9.0 \cdot 10^{-4}$
2000	0.080	0.088	1.3	0.57	0.027
1500	0.060	0.51	5.7	2.7	0.18
1200	0.24	1.7	15.3	7.6	0.63
1000	0.68	4.0	32	17	1.7
800	2.2	11	76	42	4.9
600	8.7	37	220	120	18
500	19	77	410	240	39
400	49	180	880	530	94
300	150	550	$2.3 \cdot 10^3$	$1.4 \cdot 10^3$	290

Table 5. The same for LHC (set 1, $\sqrt{s} = 15 Tev$)

M(Gev)	σ_{cc}	σ_{ss}	σ_{uu}	σ_{dd}	σ_{sc}
4000	$2.9 \cdot 10^{-7}$	0.00092	0.062	0.016	0.0054
3000	$0.70 \cdot 10^{-4}$	0.012	0.37	0.14	0.0036
2000	0.0059	0.23	3.5	1.5	0.044
1500	0.063	1.3	14	6.3	0.42
1200	0.30	4.1	34	17	1.2
1000	0.94	10	70	36	3.6
800	3.4	27	160	86	8.1
600	15	90	440	250	32
500	35	180	830	490	71
400	95	430	$1.7 \cdot 1063$	$1.1 \cdot 10^3$	180

Table 6. The same for LHC (set 2, $\sqrt{s} = 15 Tev$)

M(Gev)	σ_{cc}	σ_{ss}	σ_{uu}	σ_{dd}	σ_{sc}
4000	$2.5 \cdot 10^{-4}$	0.0067	0.12	0.045	0.0013
3000	0.0027	0.056	0.71	0.31	0.013
2000	0.051	0.59	5.1	2.5	0.17
1500	0.28	2.3	17	8.7	0.80
1200	0.91	6.1	39	21	2.4
1000	2.2	13	75	42	5.3
800	6.3	31	160	95	14
600	22	94	440	260	45
500	45	190	810	500	93
400	110	420	$1.7 \cdot 10^3$	$1.1 \cdot 10^3$	210

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